

# Design of a far-infrared spectrometer for atmospheric thermal emission measurements

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## ABSTRACT

Global measurements of far infrared emission from the upper troposphere are required to test models of cloud radiative forcing, water vapor continuum emission, and cooling rates. Spectra with adequate resolution can also be used for retrieving atmospheric temperature and humidity profiles, and yet there are few spectrally resolved measurements of outgoing longwave flux at wavelengths longer than  $16\ \mu\text{m}$ . It has been difficult to make measurements in the far infrared due to the need for liquid-helium cooled detectors and large optics to achieve adequate sensitivity and bandwidth. We review design considerations for infrared Fourier transform spectrometers, including the dependence of system performance on basic system parameters, and discuss the prospects for achieving useful sensitivity from a satellite platform with a lightweight spectrometer using uncooled detectors.

**Keywords:** Fourier transform spectrometers; infrared spectroscopy; atmospheric remote sensing; atmospheric temperature; atmospheric humidity; radiative transfer

## 1. INTRODUCTION

Fourier transform spectrometers (FTS) operating in the far infrared (FIR; defined here as wavelengths longer than  $16\ \mu\text{m}$ ) have generally used cooled detectors, either photoconductors operating at 4.2 K or bolometers operating at even colder temperatures. The low temperatures are required both to achieve useful sensitivity and, in the case of a scanning FTS, to provide the necessary electronic bandwidth. Recent improvements in the sensitivity and bandwidth of uncooled detectors have motivated us to reconsider the possibility of demonstrating useful sensitivity with an FTS operating in the FIR with uncooled detectors.

In the following sections we derive a general expression for the sensitivity of a Fourier transform spectrometer as a function of basic system parameters. We then estimate the sensitivity that can be achieved with the present generation of uncooled detectors, and the improvement in performance that could be realized with detectors operating at the thermal noise limit.

## 2. INTERFEROGRAM

We consider first a conventional scanning FTS, shown schematically in Figure 1. For a monochromatic source the interferometer output is given by

$$I(x) = I_0 + 0.5\eta(k)S_d \cos(2\pi kx), \quad (1)$$

where  $I(x)$  is the output power,  $x$  is the optical path difference (OPD) between the two arms of the interferometer,  $I_0 \equiv S_2 + 0.5\eta(k)S_d$ ,  $S_d \equiv S_1 - S_2$ ,  $\eta(k) \equiv 4R(k)T(k)$ ,  $S_1$  and  $S_2$  are the power at each input,  $k$  is the wavenumber (1/wavelength), and  $R(k)$  and  $T(k)$  are the beamsplitter reflectance and transmittance, respectively.

For a broadband source the interferogram is given by the integral of Equation (1) as shown below:

$$I(x) = I_0 + 0.5 \int_{-\infty}^{+\infty} dk \eta(k) S_d(k) \cos(2\pi kx), \quad (2)$$

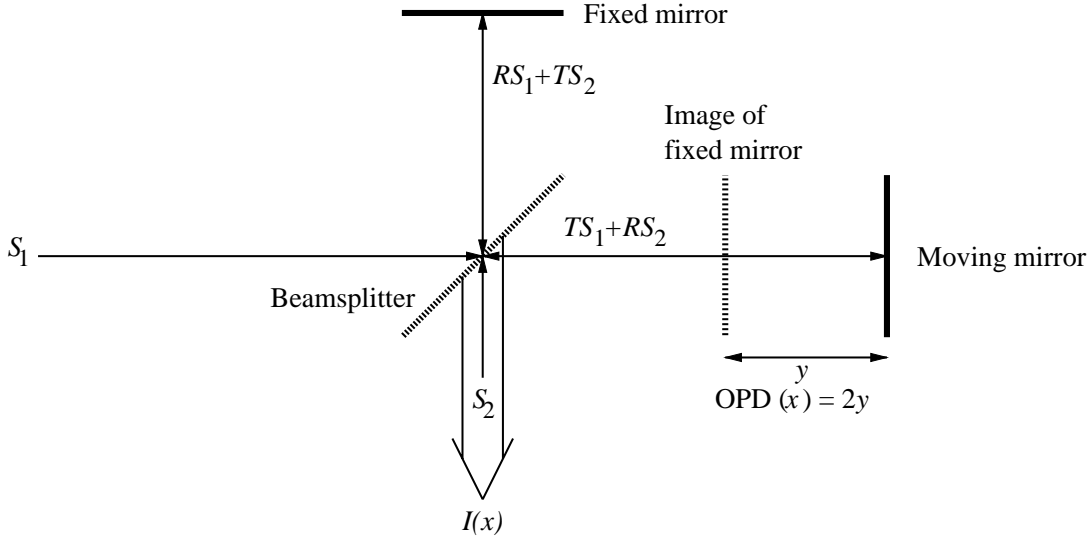
$$I_0 \equiv \int_{-\infty}^{+\infty} dk [S_2(k) + 0.5\eta(k)S_d(k)]; \quad (3)$$

where  $S_d(k)$ , the net input spectral power per unit wavenumber interval, is given by  $S_1(k) - S_2(k)$ , and  $S_1(k)$  and  $S_2(k)$  are the spectral power per unit wavenumber interval at inputs 1 and 2, respectively.

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**Figure 1.** Generic Fourier transform spectrometer layout.

We estimate the net input spectrum by taking the Fourier transform of Equation (2) after subtracting the constant term  $I_0$ :

$$S'_d(k) = \int_{-\infty}^{+\infty} dx \exp(2\pi i k x) \int_{-\infty}^{+\infty} dk' 0.5\eta(k') S_d(k') \cos(2\pi k' x), \quad (4)$$

$$= 0.5\eta(k) S_d(k); \quad (5)$$

where  $S'_d(k)$  is the estimated net input spectrum.

In practice the inputs  $S_1$  and  $S_2$  (or the output  $I(x)$ ) are optically filtered to produce a band-limited interferogram, and we further reduce the noise by passing the detector output through an electronic filter matched to the optical bandpass and mirror scan velocity. We then estimate  $S'_d(k)$  from the discrete Fourier transform (DFT) of the band-limited interferogram<sup>1</sup>:

$$S'_d(k_n) \approx \Delta H_n; \quad (6)$$

$$H_n \equiv \sum_{j=-N/2}^{N/2-1} \exp(2\pi i k_n x_j) (I_j - I_0), \quad (7)$$

where  $H_n$  is the DFT of  $(I_j - I_0)$ ,  $I_j \equiv I(x_j)$ ,  $x_j \equiv j\Delta$ ,  $k_n \equiv n/N\Delta$ ,  $N$  is the total number of samples, and  $\Delta$  is the difference in optical path between interferogram samples. Note that we have assumed that the interferogram is fully two-sided,

We combine Eqs. (5) and (6) to solve for  $H_n$  as a function of the net input power per unit wavenumber:

$$H_n \approx 0.5\eta(k) S_d(k_n) / \Delta. \quad (8)$$

To estimate the response of a particular interferometer to an input of known net spectral intensity we need to consider optical throughput and spectral response of the detector. To simplify the present discussion we assume that the spectrometer fully illuminates a detector of area  $A$  with a beam having the focal ratio  $f$ , and that the spectral response of the detector, filters, and other optics (except the beamsplitter) is represented by a single efficiency  $\epsilon(k)$ . The effective (detected) net spectral power per unit wavenumber ( $S_d$ ) is given by:

$$S_d(k) = \epsilon(k) F_d(k) \pi A / 4 f^2, \quad (9)$$

where  $F_d$  is the net input spectral intensity.

### 3. NOISE

We now consider the effect of noise on the interferogram. We assume that noise is given by the function  $g(x)$ , and that the observed interferogram is given by  $I(x) + g(x)$ . We define  $g_j \equiv g(x_j)$ , where  $x_j$  is defined above. The variance in the DFT of  $g_j$  is related to the variance of  $g_j$  by the discrete version of Parseval's Theorem<sup>1</sup>:

$$\text{Var}(G_n) = N\text{Var}(g_j), \quad (10)$$

where  $G_n$  is the DFT of  $g_j$ ,  $\text{Var}(y)$  signifies the variance of  $y$ , and  $N$  is defined above. The variance of  $g_j$  is related to the specific detectivity and electronic bandwidth of the detector and preamplifier as follows:

$$\text{Var}(g_j) = A v_B / (D^*)^2, \quad (11)$$

where  $v_B$  is the preamplifier bandwidth and  $D^*$  is the specific detectivity of the detector. After substituting Equation (11) in Equation (10) and taking the square root we derive the result

$$\sigma = \sqrt{N A v_B} / D^*, \quad (12)$$

where  $\sigma \equiv \sqrt{\text{Var}(G_n)}$ . Note that both  $G_n$  and  $H_n$  are complex (having both real and imaginary components), while  $g_j$  and the original spectrum  $S_d$  are real. We can reduce  $\sigma$  by an additional factor of  $\sqrt{2}$  by properly phase correcting the spectrum (calculating  $\Re\{H_n \exp[i\phi(k_n)]\}$ , where the phase function  $\phi(k_n)$  can be estimated in a number of ways<sup>2</sup>), since half the variance in  $G_n$  corresponds to the imaginary component of  $S_d$  and can be removed.

The signal-to-noise ratio (SNR) is given by  $H_n / \sigma$ . Substituting Eqs. (8) and (12) for  $H_n$  and  $\sigma$ , respectively, we derive the result

$$\text{SNR} = 0.5 D^* \eta(k) S_d(k) / \Delta \sqrt{N A v_B}. \quad (13)$$

Note that the unapodized spectral resolution of a transformed two-sided interferogram of length  $N$  is given by  $1/N\Delta$ . We now assume that  $v_B$  is equal to the Nyquist frequency (meaning that we sample the interferogram at exactly  $2v_B$ ) so that the time required to record one interferogram is given by  $N/2v_B$ . We define  $\delta k \equiv 1/N\Delta$  and  $\tau \equiv N/2v_B$ . After combining Eqs. (9) and (13) and substituting for  $\tau$  and  $\delta k$ , we derive the result

$$\text{SNR} = \pi \epsilon(k) D^* \eta(k) F_d(k) \delta k \sqrt{2\tau A} / 8f^2. \quad (14)$$

### 4. SENSITIVITY

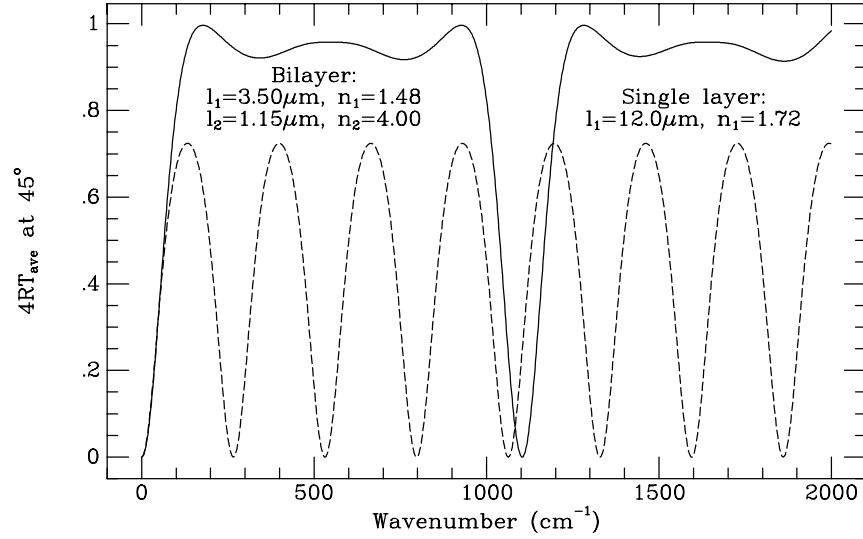
The sensitivity (NEdP) is given by  $F_d / \text{SNR}$ , or

$$\text{NEdP} = 8f^2 / \pi \epsilon D^* \eta(k) \delta k \sqrt{2\tau A}, \quad (15)$$

where NEdP is expressed in units of power per unit area per unit solid angle per unit wavenumber interval. The minimum detectable change in temperature is given by  $\text{NEdP} / (dF/dT)$ , where  $dF/dT$  is the derivative with respect to temperature of the spectral intensity of a blackbody source. While NEdP depends only on the characteristics of the spectrometer and detector, NEdT also depends on the assumed source temperature.

We now consider the steps that can be taken to maximize the sensitivity of an FTS operating in the FIR with uncooled detectors. To be more specific, we will consider an imaging FTS in low earth orbit. The instrument is to provide spectra covering the wavelength range 10–100  $\mu\text{m}$  with 0.6  $\text{cm}^{-1}$  resolution (apodized), daily global coverage, and a  $10 \times 10$  km footprint. The detectivity of uncooled far-infrared detectors depends on detector temperature and is independent of source intensity,<sup>3</sup> so that we may assume that each of the terms in Equation (15) is independent.

The need for daily global coverage and a small footprint greatly limits the integration time  $\tau$ . Observing the entire globe with a 100  $\text{km}^2$  footprint once a day means that the spectrometer must provide five million spectra per day, corresponding to 17 ms per spectra if they are obtained one at a time. To obtain the desired resolution of 0.6  $\text{cm}^{-1}$  (corresponding to  $\delta k = 0.3 \text{ cm}^{-1}$ ) in 17 ms we must scan the interferometer mirror at 98 cm/s, resulting in an electronic frequency of 98 kHz at a wavelength of 10  $\mu\text{m}$ . Available uncooled IR detectors simply do not provide adequate sensitivity at such high modulation frequencies. However, by going to a modest  $10 \times 10$  array of detectors we increase the integration time and reduce the modulation frequency by a factor of 100 to a more reasonable 980 Hz. The penalty is that the FTS throughput must also be increased by a factor



**Figure 2.** Comparison of conventional and bilayer pellicle beamsplitter. The conventional beamsplitter consists of an uncoated  $12\text{ }\mu\text{m}$  thick Mylar film, while the bilayer beamsplitter consists of  $3.5\text{ }\mu\text{m}$  of polypropylene coated with  $1.15\text{ }\mu\text{m}$  of germanium.

of 100, although this is not an insurmountable problem. In the discussion that follows we assume that the FTS illuminates a  $10 \times 10$  array, giving us 1.7 s per field, and that of that 1.7 s we have 1.4 s available to record the interferogram. This gives  $\tau = 1.4\text{ s}$  and  $\nu_B = 1200\text{ Hz}$  for a minimum wavelength of  $10\text{ }\mu\text{m}$ .

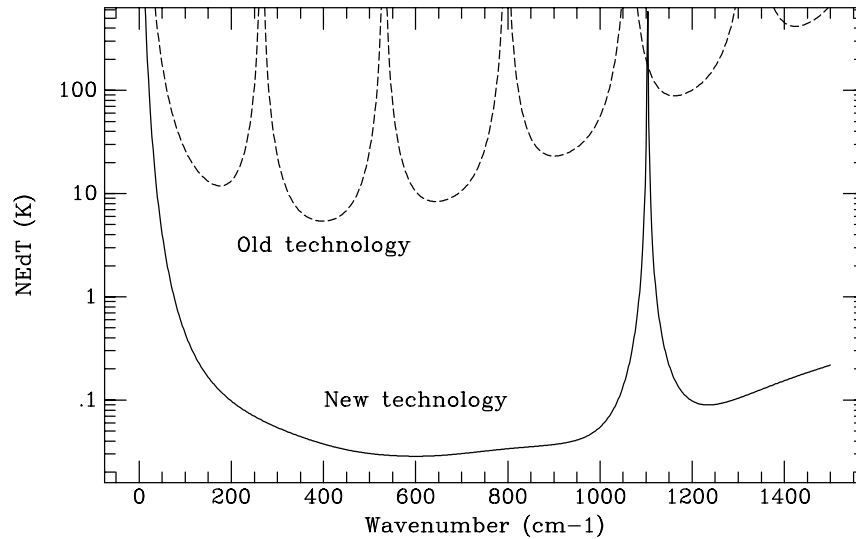
Clearly the detector needs to be illuminated with the fastest possible optical system since NEdP is proportional to  $f^2$ . The best that can be done with a reflective off-axis system is about  $f = 2$ . While an on-axis  $f = 1$  refractive system could be built, it is unlikely that such a system could be color-corrected over the desired optical band. However, one can do much better with non-imaging reflective systems. A parabolic feed horn<sup>4</sup> provides the maximum possible flux concentration, achieving  $f = 0.5$ . Such feed horns are commonly used with liquid-helium cooled FIR detectors. Decreasing the focal ratio by a factor of 4 improves the sensitivity by a factor of 16.

The beamsplitter must provide the highest possible efficiency. Uncoated pellicle beamsplitters provide rather low average efficiency (typically  $\eta \approx 0.46$ ), although the efficiency is higher in narrow bands. Improved beamsplitters can be manufactured by depositing coatings on thick substrates, but substrates lacking significant absorption from  $10\text{--}100\text{ }\mu\text{m}$  do not exist. Polarizing beamsplitters can provide ideal efficiency in a properly designed (Martin-Puplett) FTS, but such designs have yet to demonstrate adequate performance at wavelengths as short as  $10\text{ }\mu\text{m}$ . However, bilayer pellicle beamsplitters<sup>5</sup> can provide nearly ideal performance over the desired band, as shown in Figure 2.

The sensitivity can be increased somewhat by using larger detectors, but in practice the detector size is limited by the ability to design a spectrometer with sufficient throughput to fully illuminate a  $10 \times 10$  array of detectors with a fast beam. Larger detectors also tend to have longer thermal time constants and thus have insufficient bandwidth for use in a scanning FTS.

The best presently available uncooled IR detectors at high frequencies ( $> 100\text{ Hz}$ ) are pyroelectric detectors. A  $1\text{ mm}^2$  detector can be obtained with  $D^* = 1.5 \times 10^9\text{ cm Hz}^{0.5}/\text{W}$  at  $100\text{ Hz}$ , dropping to  $2 \times 10^8$  at a kilohertz. This is still an order of magnitude or more less than the thermal noise limit of  $1.8 \times 10^{10}$  for an uncooled detector.<sup>3</sup>

The increases in sensitivity that may be realized are shown in Figure 3. For both calculations we assume  $\tau = 1.4\text{ s}$ ,  $\epsilon = 1.0$ ,  $\delta k = 0.3\text{ cm}^{-1}$ , and a scene temperature of  $230\text{ K}$ . For the conventional technology we use the Mylar beamsplitter shown in Figure 2 and the  $1\text{ mm}^2$  pyroelectric detector described above, illuminated by an  $f = 2$  beam. For the proposed technology we use the bilayer beamsplitter and a thermal noise limited detector illuminated by a parabolic feed horn. We assumed a feed horn with an input focal ratio of 4 and an input area of  $1\text{ mm}^2$ . The output focal ratio is 0.5 and illuminates a detector area of  $0.0625\text{ mm}^2$  (required to conserve  $A\Omega$ ).



**Figure 3.** Comparison of predicted performance with conventional and proposed technologies described in the text.

## 5. CONCLUSION

A space-borne imaging FTS has been proposed that can provide spectra covering the wavelength range 10-100  $\mu\text{m}$  with  $0.6\text{ cm}^{-1}$  resolution, daily global coverage, a 10 km footprint, and an NEDT of better than 0.1 K from 10-50  $\mu\text{m}$ . The proposed instrument requires infrared detectors that are thermal noise limited at ambient temperatures. Such detectors are an order of magnitude more sensitive than the best detectors presently available.

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